
PART 2

LM3-EUTRO

Chapter 7. Results – Application of Model

A total of seven model scenarios were run to evaluate future lake conditions under different total phosphorus loads. Because total phosphorus is not a model state variable, the individual phosphorus state variables (soluble reactive phosphorus [SRP], dissolved organic phosphorus [DOP], labile organic phosphorus [LOP], and refractory organic phosphorus [ROP]) were scaled accordingly to accomplish the total phosphorus load increases or reductions. The assumptions and conditions for each model scenario are briefly described followed by a Results and Discussion section. We evaluated future lake-wide total phosphorus and particulate organic carbon (POC) concentrations as well as epilimnetic and hypolimnetic chlorophyll concentrations (assuming a 20 m thermocline). Model simulation time for the scenarios ranged between 20 and 30 years, with scenarios starting in 1994 and load increases and decreases beginning in 2005.

2.7.1 Scenario 1 – Constant Conditions

2.7.1.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. Total phosphorus tributary and atmospheric loads for 1994 and 1995 were repeated in a two-year cycle. Hydrodynamics for 1994 and 1995 were similarly repeated. The model was run until steady-state was achieved.

2.7.1.2 Results and Discussion

The model reached steady-state within 28 years (2021). The steady-state lake-wide concentrations for total phosphorus and maximum POC were 4.3 µg/L and 0.2 mg/L, respectively (Figure 2.7.1), while the values for the spring maximum chlorophyll *a* concentrations were 2.36 µg/L for the epilimnion and 1.07 µg/L for the hypolimnion (Figure 2.7.1).

2.7.2 Scenario 2 – Virtual Elimination (Lower Bound)

2.7.2.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004. Beginning on January 1, 2005, tributary and atmospheric total phosphorus loads were reduced by 100% and the sediment total phosphorus fluxes were assumed to be zero. The model was run for a total of 30 years (through December 2023).

2.7.2.2 Results and Discussion

As expected, the total phosphorus concentration significantly declined once the atmospheric and tributary total phosphorus loads were turned off. The model predicted that after 30 years (December 2023), the lake-wide total phosphorus concentration would be 0.54 µg/L (Figure 2.7.2). The epilimnetic maximum chlorophyll *a* concentration after 30 years would be less than 0.1 µg/L, while the hypolimnetic

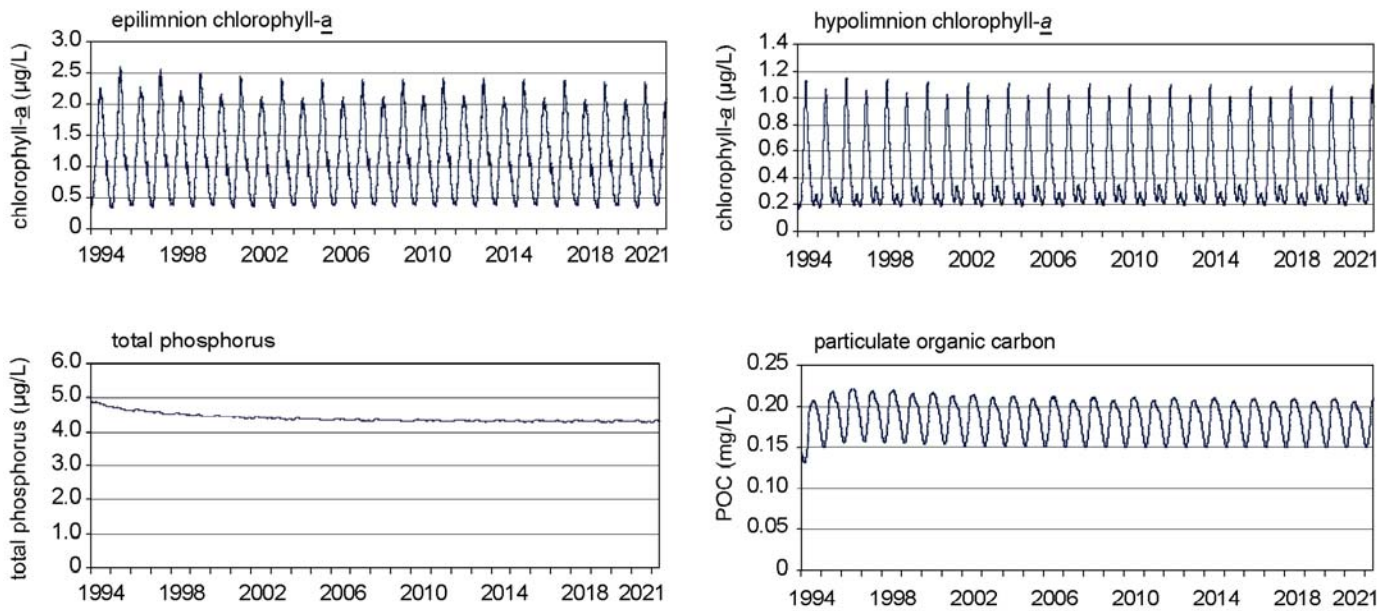


Figure 2.7.1. Scenario 1: Constant Conditions.

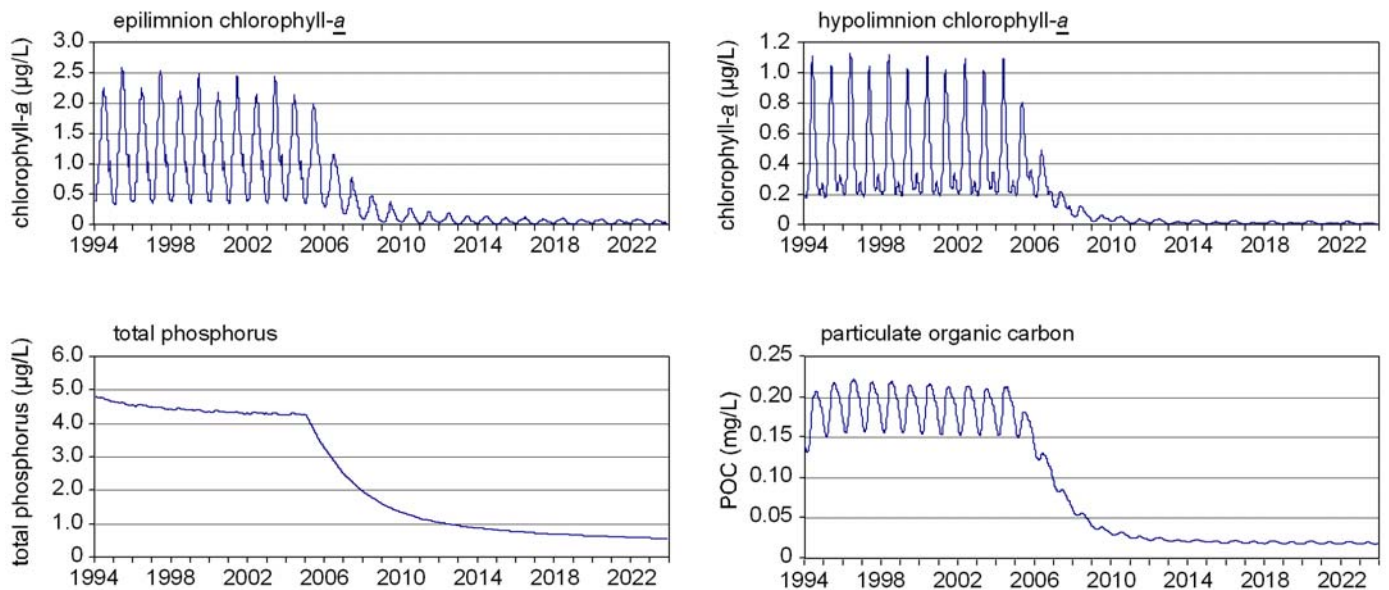


Figure 2.7.2. Scenario 2: Virtual elimination.

concentration would be approaching zero (Figure 2.7.2). In 2023, the lake-wide POC concentration maximum was around 0.02 mg/L (Figure 2.7.2).

2.7.3 Scenario 3 – Best Estimate of Current Trends Resulting From Previous Actions

2.7.3.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. Tributary and atmospheric total phosphorus loads declined at rates observed over the last two decades (1981-1995). The model was run for a total of 20 years (through December 2013).

The rate of total phosphorus decay was based on the downward trend of total phosphorus in Lake Michigan since the 1980s. In order to calculate the decay, it was assumed that the total phosphorus equation was an exponential. Figure 2.7.3 shows the Lake Michigan historical total phosphorus loading. Although historical total phosphorus loading data

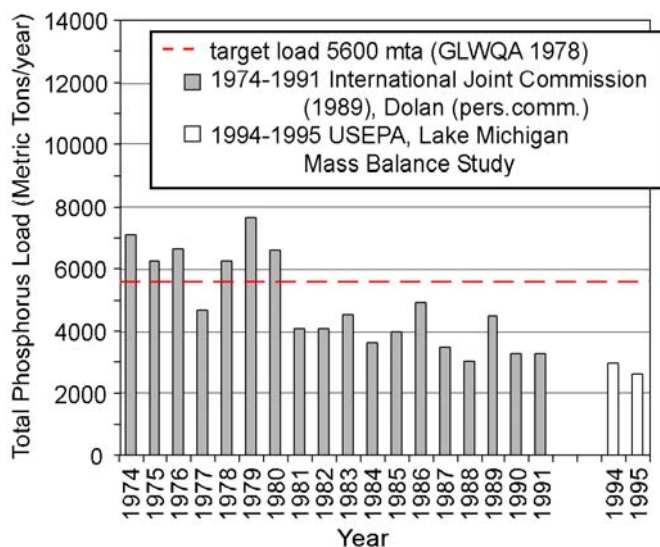


Figure 2.7.3. Historical total phosphorus loading – Lake Michigan.

prior to 1981 were available, only the loading values between 1981 and 1995 were used because it was believed this provided the most realistic picture of the

present loading trend. No loading data were available after 1995. Total phosphorus loads were assumed to follow the equation:

$$L(t) = L(t_0) \exp[k(t - t_0)] \quad (2.7.1)$$

where

t = time in units of years

t_0 = initial time (1981)

$L(t)$ = total phosphorus load at time t

$L(t_0)$ = total phosphorus load at time t_0

k = total phosphorus decay rate in units of 1/year.

The decay rate k was calculated by applying the Least Squares Fitting method and has a value of -2.21×10^{-2} /year.

2.7.3.2 Results and Discussion

The total phosphorus concentration steadily declined over 20 years to approximately 3.5 $\mu\text{g/L}$ (Figure 2.7.4). The epilimnetic chlorophyll a reached a value of approximately 2.0 $\mu\text{g/L}$, while the hypolimnion fell below 0.9 $\mu\text{g/L}$ (Figure 2.7.4). In 2013, the lake-wide POC maximum concentration was around 0.18 mg/L (Figure 2.7.4).

2.7.4 Scenario 4 – Scenario 1 With Instantaneous Reduction of Tributary Loads to Zero

2.7.4.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004. Beginning on January 1, 2005, tributary total phosphorus loads were reduced by 100%. The 1994 and 1995 atmospheric load cycle was continued. The model was run for a total of 30 years (through December 2023).

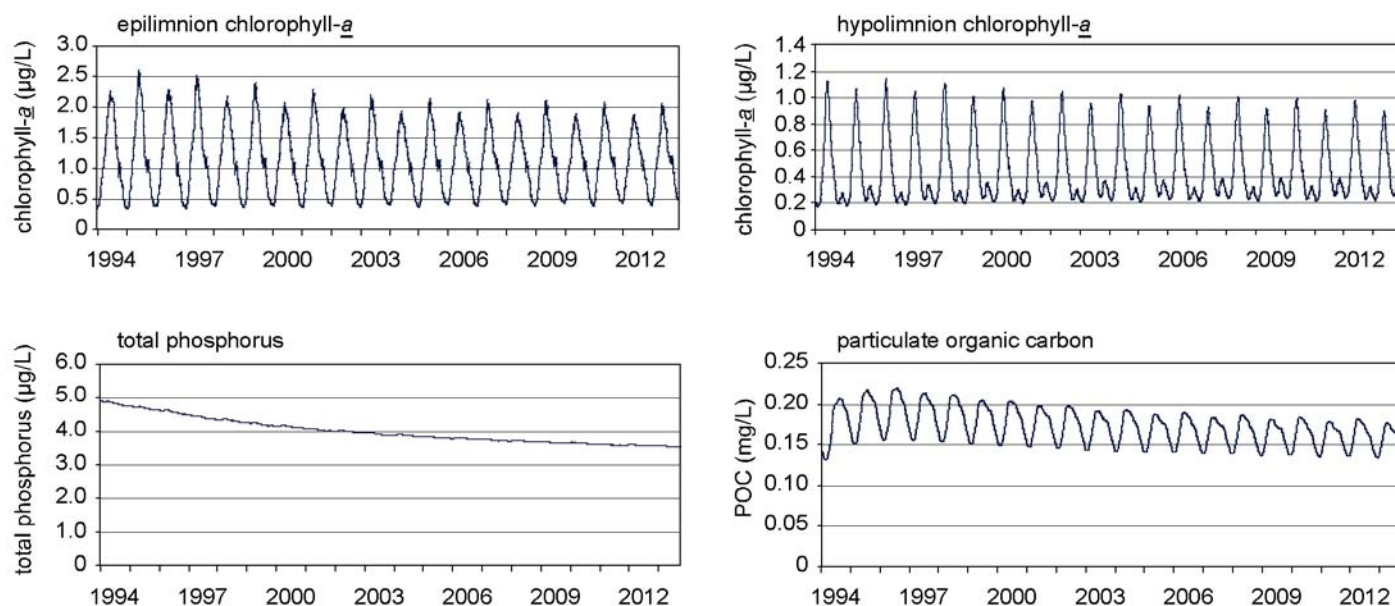


Figure 2.7.4. Scenario 3: Best estimate of current trends resulting from previous actions.

2.7.4.2 Results and Discussion

There was a significant decline in the total phosphorus concentration when the tributary loads were turned off in January 2005 (Figure 2.7.5).

However, this decline was not as steep as that observed in Scenario 2 (Virtual Elimination). The total phosphorus concentration at the end of 2023 was 0.91 µg/L, which was higher than the 0.54 µg/L observed in the Virtual Elimination scenario (Scenario 2). Similarly, after 30 years, the maximum chlorophyll *a* concentration fell to approximately 0.4 µg/L and less than 0.1 µg/L for the epilimnion and hypolimnion, respectively (Figure 2.7.5), and the lake-wide POC maximum was 0.03 mg/L (Figure 2.7.5). These values were all somewhat higher than their equivalents in Scenario 2.

2.7.5 Scenario 5 – Scenario 1 With Instantaneous Reduction of Atmospheric Loads to Zero

2.7.5.1 Description of Assumptions

The scenario was started in January 1, 1994. A constant user-specified net sediment total

phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004. Beginning on January 1, 2005, atmospheric total phosphorus loads were reduced by 100%. The 1994 and 1995 tributary load cycle was continued. The model was run for a total of 20 years (through December 2013).

2.7.5.2 Results and Discussion

Turning off the atmospheric total phosphorus loads had little effect on the total phosphorus, chlorophyll *a*, and POC concentration (Figure 2.7.6) as compared to the Constant Conditions scenario (Figure 2.7.1).

2.7.6 Scenario 6 – Scenario 1 With Tributary and Atmospheric Loads Increased 20%

2.7.6.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004.

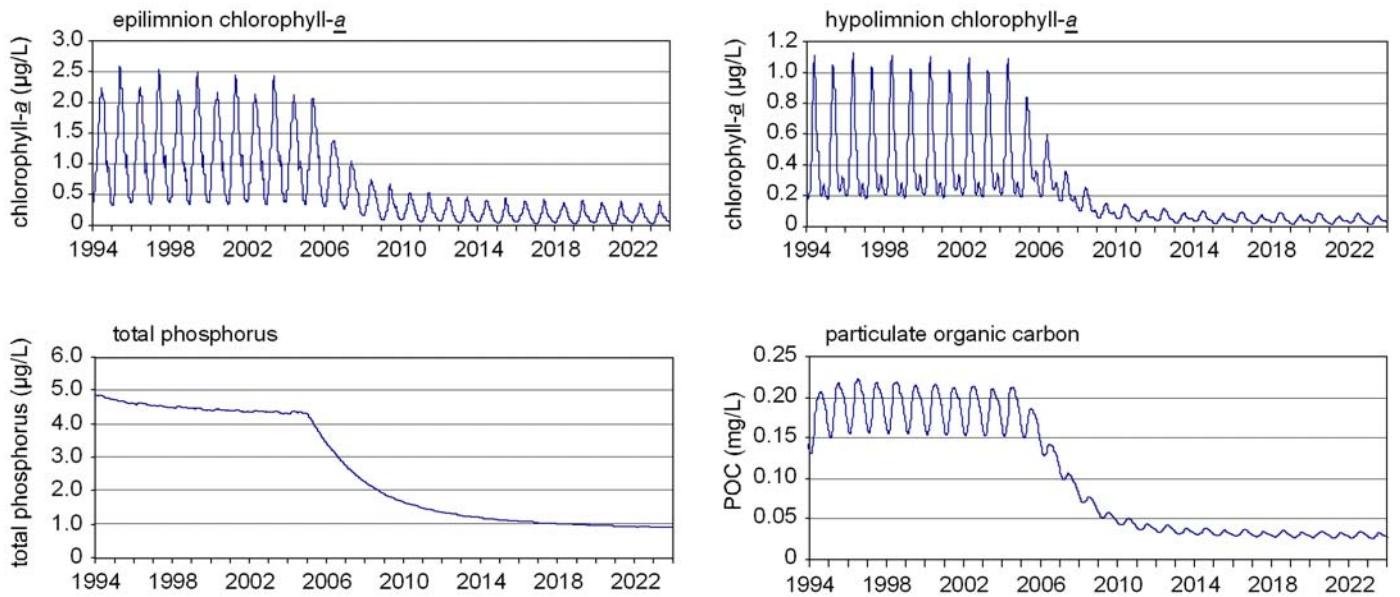


Figure 2.7.5. Scenario 4: Scenario 1 with tributary load elimination.

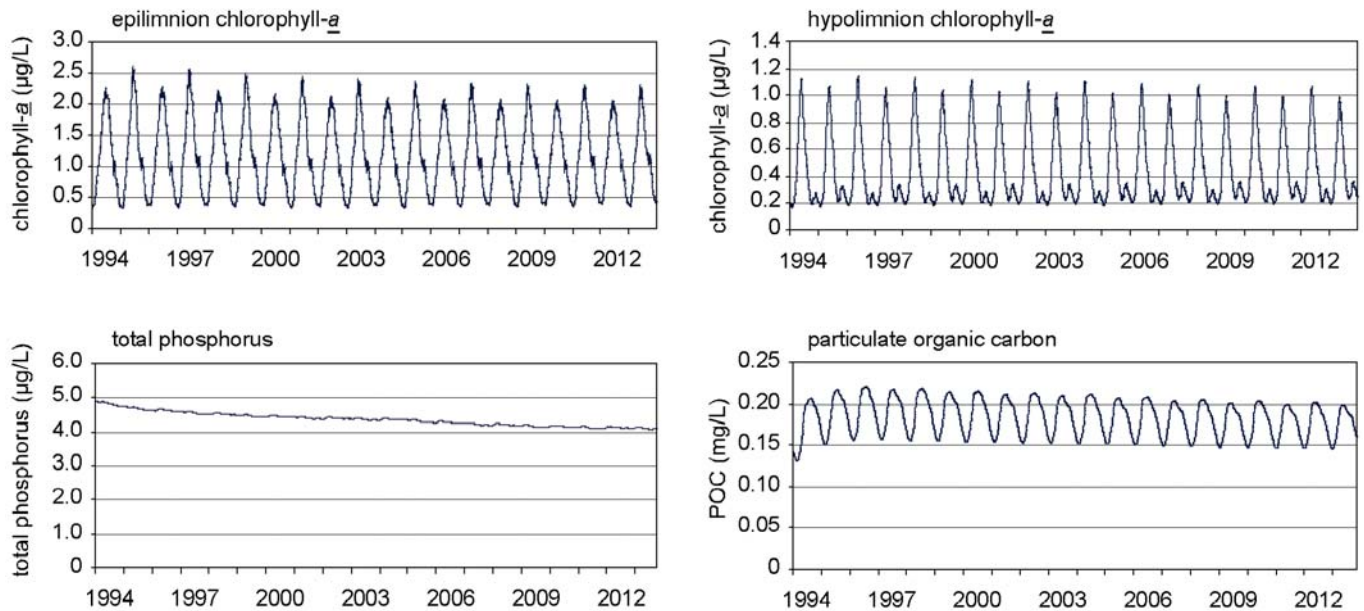


Figure 2.7.6. Scenario 5: Scenario 1 with atmospheric load elimination.

Beginning on January 1, 2005, tributary and atmospheric total phosphorus loads were increased by 20%. The model was run for a total of 20 years (through December 2013).

2.7.6.2 Results and Discussion

The 20% increase in total phosphorus loads had a relatively small influence on the total phosphorus concentration, the epilimnetic chlorophyll *a* concentration, and the POC concentration (compare Figure 2.7.7 [20% load increase] with Figure 2.7.1 [Constant Conditions]). The lake-wide total phosphorus concentration after 20 years was 4.6 $\mu\text{g/L}$ (Figure 2.7.7). Maximum chlorophyll *a* concentrations after 20 years were 2.2-2.5 $\mu\text{g/L}$ (epilimnion) and 1.1 $\mu\text{g/L}$ (hypolimnion) (Figure 2.7.7). The lake-wide POC maximum concentration was 0.22 mg/L (Figure 2.7.7).

2.7.7 Scenario 7 – Application of Great Lakes Water Quality Agreement Loads to Model

2.7.7.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004. Beginning on January 1, 2005, the 1978 Great Lakes Water Quality Agreement (GLWQA) specified total phosphorus target loading of 5,600 MT/year was applied (International Joint Commission, 1978). The 1994 and 1995 atmospheric load cycle was continued. A new user-defined net sediment total phosphorus flux was estimated, assuming that approximately 95% of the phosphorus load was retained in the sediment and 5% was recycled back to the water column. The model was run to steady-state.

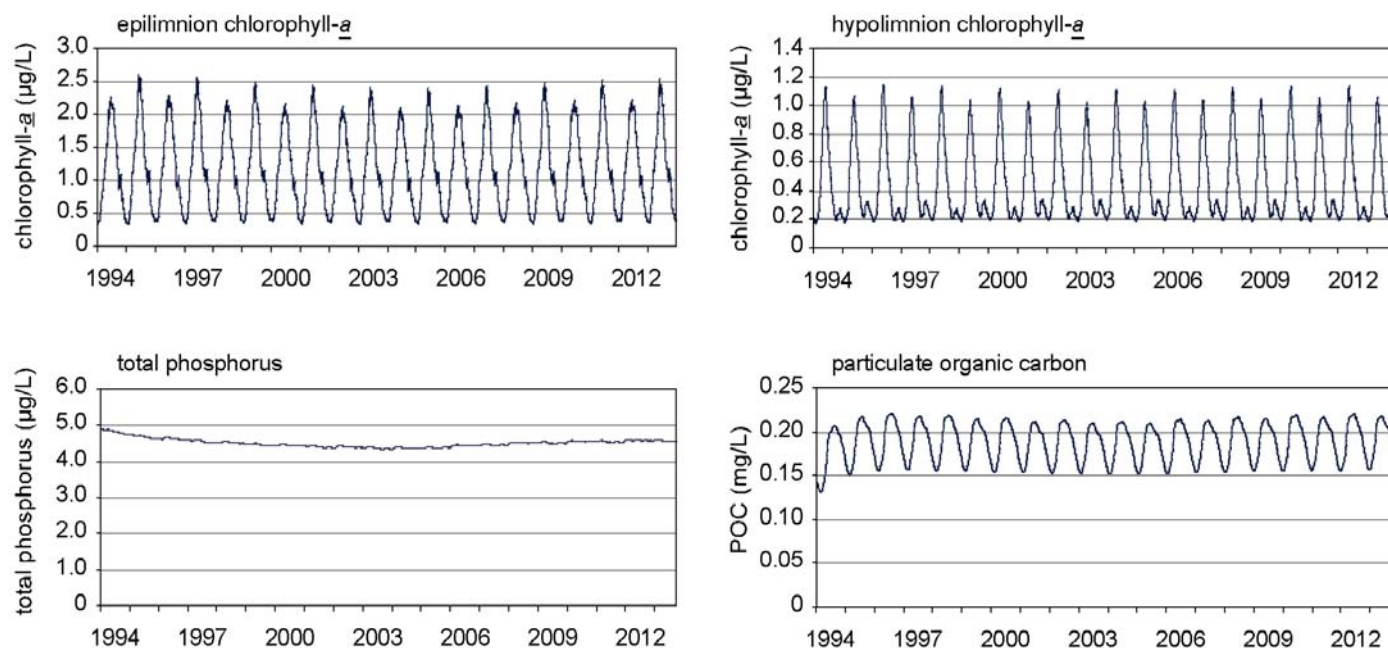


Figure 2.7.7. Scenario 6: Scenario 1 with tributary and atmospheric loads increased 20%.

2.7.7.2 Results and Discussion

Applying the GLWQA total phosphorus load of 5,600 MT/year resulted in a lake-wide steady-state total phosphorus concentration of 7.5 µg/L and an epilimnetic chlorophyll *a* maximum of 4.0 µg/L (Figure 2.7.8). The hypolimnetic chlorophyll *a* maximum at steady-state was 1.6 µg/L (Figure 2.7.8). Steady-state lake-wide maximum POC was approximately 0.28 mg/L (Figure 2.7.8). Steady-state was reached within 30 years.

2.7.8 Scenario 8 – Estimate of Total Maximum Daily Loads to Reach International Joint Commission’s Target Total Phosphorus Concentration

2.7.8.1 Description of Assumptions

The scenario was started on January 1, 1994. A constant user-specified net sediment total phosphorus flux was applied in both space and time. The Constant Conditions scenario (Scenario 1) was run from January 1, 1994 to December 31, 2004. Through trial-and-error, a total phosphorus load (tributary and atmospheric) that resulted in steady-state total phosphorus concentration of 7 µg/L (the lake-wide International Joint Commission’s [IJC] target) was determined (Great Lakes Research Advisory Board, 1978). A new user-defined net sediment total phosphorus flux was estimated, assuming that approximately 95% of the phosphorus load was retained in the sediment and 5% was recycled back to the water column. The IJC total phosphorus concentration target was chosen with the goal of returning Lake Michigan to its “natural oligotrophic state” under the GLWQA (International Joint Commission, 1978). The model was run to steady-state.

2.7.8.2 Results and Discussion

An average annual total phosphorus load of 5,020 MT resulted in a steady-state lake-wide total phosphorus concentration of 7 µg/L (Figure 2.7.9). This equated to a total phosphorus total maximum daily load (TMDL) of 14 MT/d. This also resulted in a spring epilimnetic maximum chlorophyll *a* concentration of 3.7 µg/L and a spring hypolimnetic chlorophyll *a* concentration of 1.6 µg/L (Figure 2.7.9).

Steady-state lake-wide maximum POC was around 0.33 mg/L (Figure 2.7.9). Steady-state was reached within approximately 30 years.

2.7.9 Scenario Comparison and Discussion

A summary of the final total phosphorus, chlorophyll *a*, and POC concentrations is shown in Table 2.7.1. Examining the scenarios revealed a number of interesting conclusions regarding Lake Michigan. It was apparent from comparing Scenarios 1, 4, and 5 that tributary loading was considerably more important than atmospheric loading in driving Lake Michigan total phosphorus and chlorophyll *a* (Figures 2.7.1, 2.7.5, and 2.7.6). However, as Scenario 6 revealed, a small increase in loading (tributary and atmospheric) does not have a large impact on the lake (Figure 2.7.7). Scenario 2 confirmed that Lake Michigan’s reaction to significant loading changes is immediate but buffered by the large water volume and slow retention time of the lake (Figure 2.7.2). Scenario 3 suggested that if current loading trends continue, lake-wide total phosphorus and chlorophyll *a* will continue to slowly decline (Figure 2.7.4). Scenarios 7 and 8 demonstrated the drastic increases in chlorophyll *a*, total phosphorus, and POC that would occur if loading to Lake Michigan were allowed to increase to GLWQA/IJC limits (Figures 2.7.8 and 2.7.9).

2.7.10 Mass Budget

The sources, sinks, and lake inventory of total phosphorus was estimated. Figure 2.7.10 is a graphical representation of the average annual loads, sinks, and total phosphorus inventory for Lake Michigan based on 1994 and 1995 modeled and measured data. It was clear that the internal recycle (settling and sediment feedback) accounted for the majority of total phosphorus dynamics occurring in the lake. A significant mass of phosphorus settled to the lake bed, but a large percentage (~ 60%) is recycled back to the water column. The monitored tributaries made up the largest external total phosphorus source to the lake, while the unmonitored tributaries and atmospheric loads were relatively small components. The total phosphorus export at the Straits of Mackinac and the Chicago diversion were estimated to be a small fraction of the

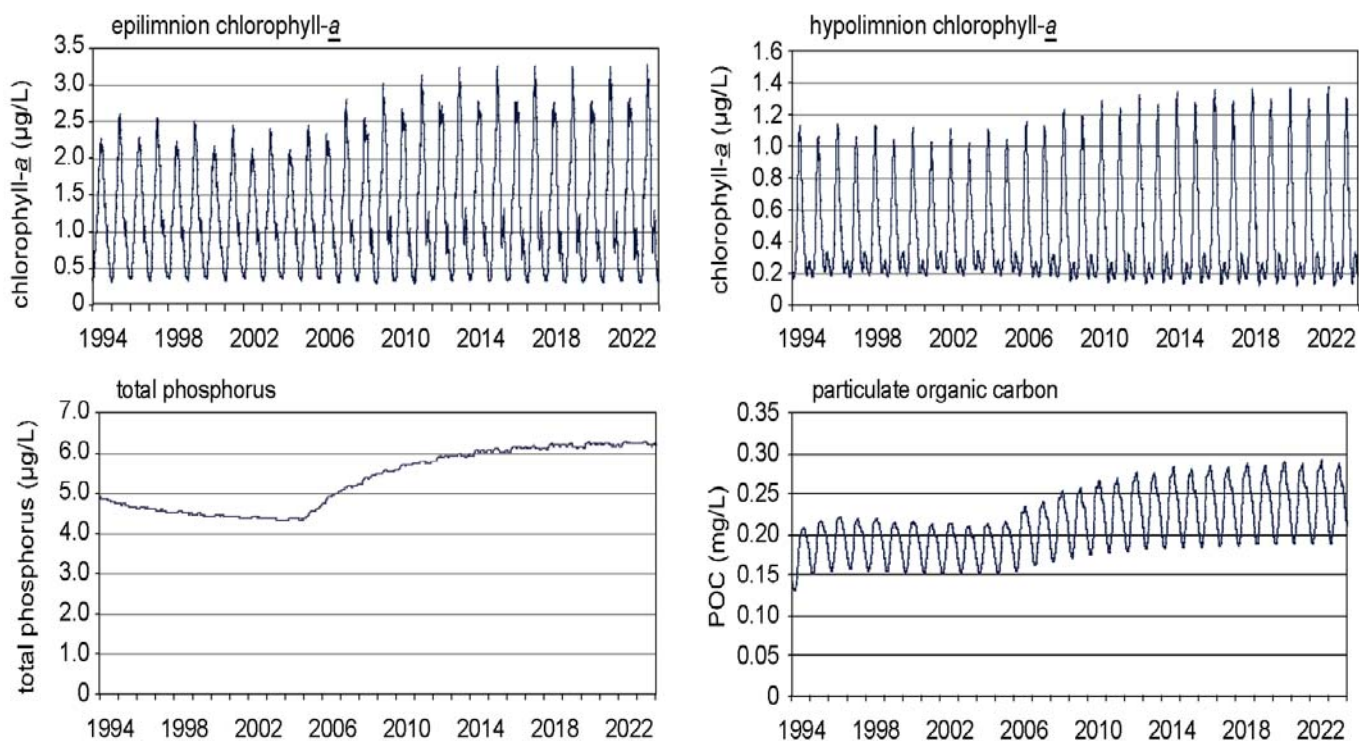


Figure 2.7.8. Scenario 7: Application of the GLWQA loads to the model.

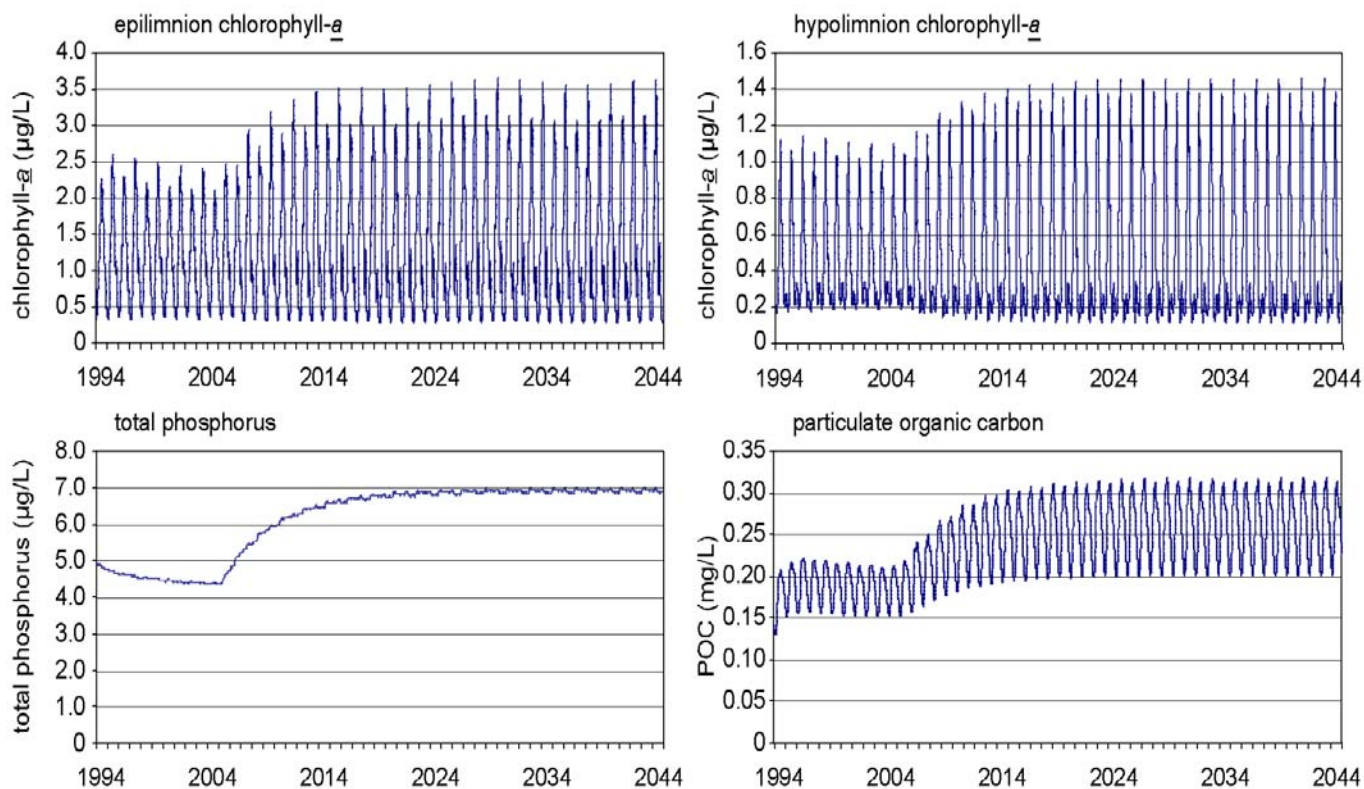


Figure 2.7.9. Scenario 8: Estimate of the TMDL to reach the IJC's target total phosphorus concentration.

Table 2.7.1. Final Eutrophication Scenario Results

Scenario and Length	Description	Spring Maximum		Total Phosphorus (µg/L)	Maximum Particulate Organic Carbon (mg/L)
		Epilimnion Chlorophyll <i>a</i> (µg/L)	Hypolimnion Chlorophyll <i>a</i> (µg/L)		
1 (28 years)	Constant Conditions Remain From 1994-1995	2.4	1.1	4.3	0.20
2 (30 years)	Virtual Elimination (Lower Bound)	0.1	~0	0.54	0.02
3 (20 years)	Best Estimate of Current Trends Resulting From Previous Actions	2.0	0.9	3.5	0.18
4 (30 years)	Scenario 1 With Instantaneous Reductions of Tributary Loads to Zero	0.4	0.1	0.91	0.03
5 (30 years)	Scenario 1 With Instantaneous Reductions of Atmospheric Loads to Zero	2.3	1.1	4.1	0.20
6 (20 years)	Scenario 1 With Tributary and Atmospheric Loads Increased 20%	2.5	1.1	4.6	0.22
7 (30 years)	Application of GLWQA Loads to Model	4.0	1.6	7.5	0.34
8 (30 years)	Estimate of TMDL to Reach IJC Target Total Phosphorus Concentration	3.7	1.6	7.0	0.33

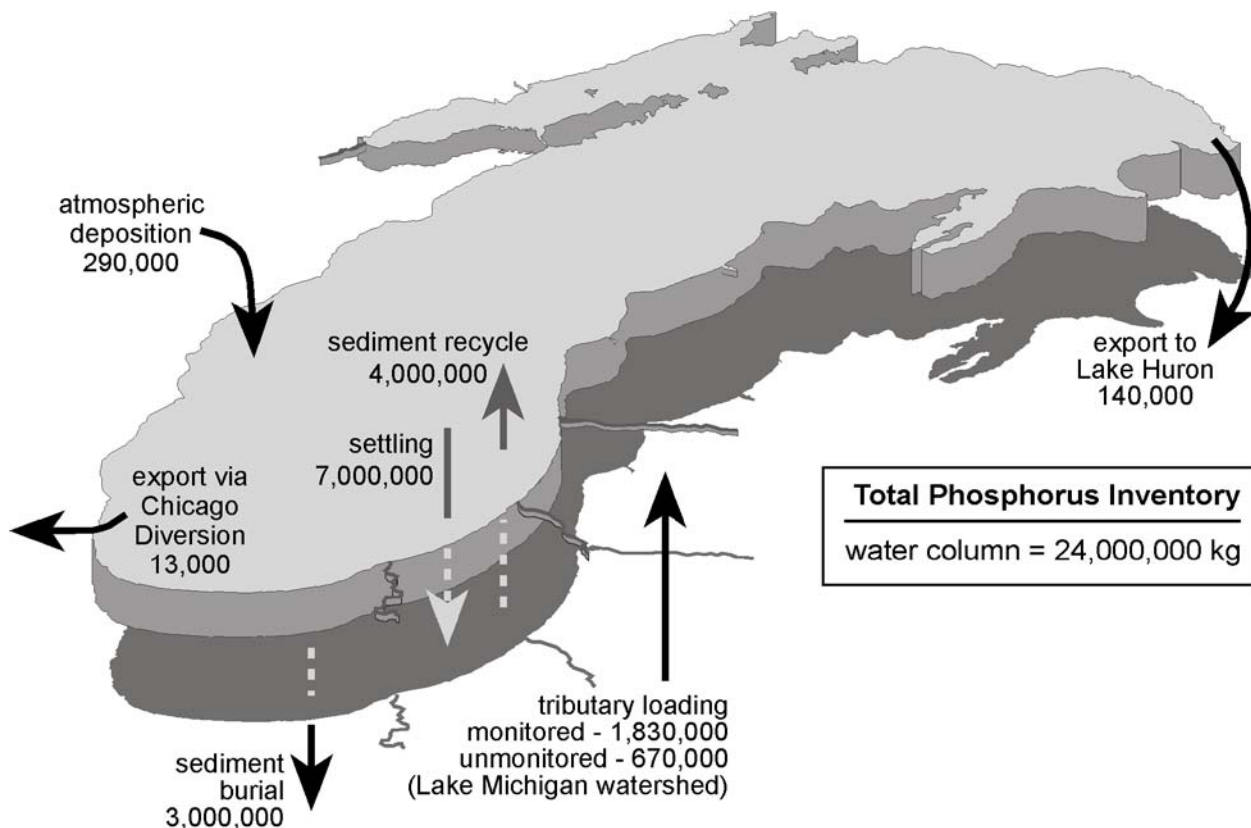


Figure 2.7.10. Annual average (1994-1995) Lake Michigan total phosphorus loading (kg/year).

total export. Overall, the best estimate using the average of the 1994-1995 loads was that there was a 5% annual loss of total phosphorus in the lake, which suggested that there would be a small, but steady, decrease in the total phosphorus lake concentration given constant total phosphorus loads. Figure 2.7.11 is a breakdown of the total phosphorus loads and inventory of the main lake and Green Bay. It depicts the loads entering the bay and lake separately and the phosphorus exchange between these two system. Phosphorus from Green Bay accounted for approximately 13% of the total phosphorus input into Lake Michigan. The bulk of the Green Bay total phosphorus load was from the Fox River.

References

- Great Lakes Advisory Board. 1978. Annual Report to the International Joint Commission. International Joint Commission, Windsor, Ontario, Canada. 44 pp.
- International Joint Commission. 1978. Great Lakes Water Quality Agreement of 1978, with Annexes and Terms of Reference, Between the United States and Canada, Signed at Ottawa, November 22, 1978. International Joint Commission, Windsor, Ontario, Canada. 60 pp.

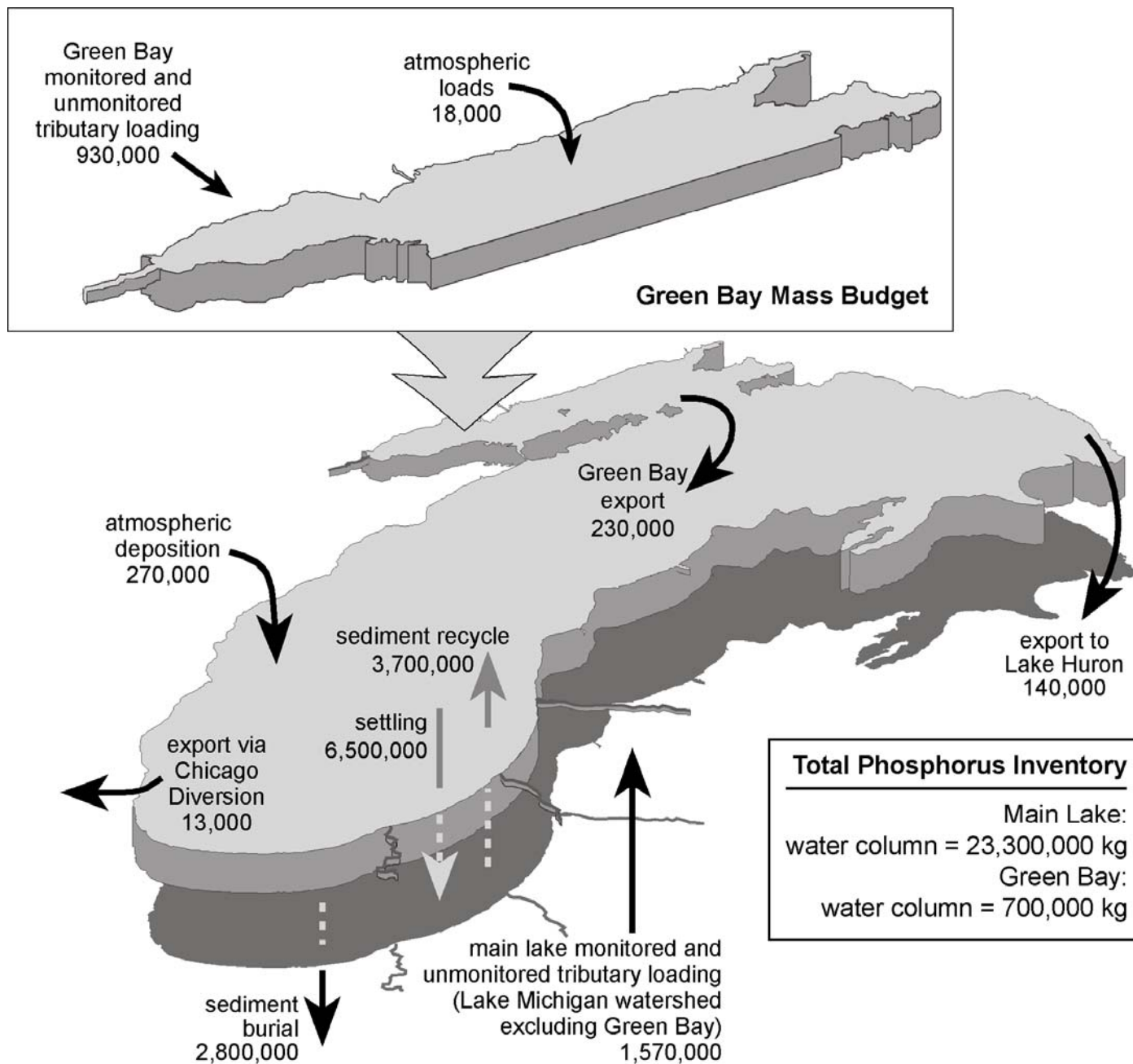


Figure 2.7.11. Annual average (1994-1995) Lake Michigan and Green Bay total phosphorus loading (kg/year).